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Review of alternative methodologies for analysing off-grid electricity supply

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ABSTRACT

Off-grid electrification is gaining importance in the developing countries where the access to electricity is often limited. The purpose of this paper is to review alternative methodologies that are used for off-grid electrification projects to identify the features of each methodological approach and to present their strengths and weaknesses. The paper reviews a large volume of relevant literature covering techno-economic feasibility studies, analytical works highlighting methodological applications and practice-oriented literature. The review identifies five methodological options, namely the worksheet-based tools, optimisation tools, multi-criteria decision-making (MCDM) tools, system-based participatory tools and hybrid approaches. The paper recommends a hybrid approach that combines two or more options to take advantage of strengths and weaknesses of different options.

Contents

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1. Introduction

The issue of providing access to electricity to almost 1.4 billion people without electricity is one of the major development challenges of recent times. Although the grid extension is the most common mode of electrification for providing electricity, the progress in this area has remained unimpressive in many countries. Accordingly, the off-grid supply is now considered as an alternative option, where renewable as well as fossil-fuel-based energies are being used either individually or in hybrid forms.

The literature on renewable energy and electricity supply for rural use is very well developed and a number of strands can be identified from this body of knowledge:

- First, the focus of most of the literature is on the technical design of the system and its cost-effectiveness analysis using some economic indicators. Given the technological diversity of renewable energies, this set of literature has often relied on the case study approach where the application of individual technologies or a combination of technologies has been considered to meet the energy demand. Some studies provide a review of the technological and economic readiness of alternative energies as well.
- Second, a number of tools have been used by various authors.
- For example, HOMER (Hybrid Optimisation Model for Electric Renewables), developed by NREL (National Renewable Energy Laboratory, USA), appears repeatedly in the literature as a preferred tool. It can handle a large set of technologies (PV, wind, hydro, fuel cells, boilers, etc.), loads (AC/DC, thermal and hydrogen), and can perform hourly simulations (see Table 1 for some applications). HOMER is an optimisation tool that is used to decide the system configuration for decentralised systems. Other software tools include HYBRID2 developed by the Renewable Energy Research Laboratory (RERL) and HOGA (Hybird Optimisation by Genetic Algorithms developed by the University of Zaragoza, Spain), which are available freely.[1]
- The use of optimisation approach has a long tradition in the energy analysis and has been extended to rural energy supply analysis by many authors. The most common application relies on linear programming due to its ease of use but more advanced applications have also been reported. In addition, computer-based dynamic economic evaluation model to assess alternative options (as in [70]) or simulation-based software for hybrid systems (as in [71]) has been reported in the literature. While some tools were technology specific [58] for an optimisation tool for wind-fuel cell hybrid), others have more generic capabilities (see [1] for a tool to assess different decentralised systems). Similarly, multi-objective evolutionary programming has been used to optimise decentralised systems (see [11] and [82] for example).
- Multi-criteria decision making and its extension to include social aspects have also found favour of analysts. Given that the decision-making often involves trade-offs amongst various competing objectives and because such decisions may change depending on the stakeholder preferences, MCDM provides an effective alternative for reconciling conflicting viewpoints.
- In addition, other methods also have been used including simple indicator-based one to more complex tools such as systems-based approaches and participatory approaches.
- Third, the practice-oriented literature (manuals, best-practice experiences, etc.) also provides some guidelines on decentralised electricity supply and in some cases recommends steps or critical factors for such projects.

Although, various approaches can be found in the literature, each method has its own features and limitation. Moreover, any solution strategy for promoting energy access has to consider various dimensions such as the techno-economic, governance, socio-political, environmental, financial, etc. The techno-economic dimension focuses on factors such as reliability of supply, sustainability of supply, cost-effectiveness and ways of improving this, manufacturing and operating capabilities, attractiveness of the supply option to the investor, and lock-in effect and its socio-economic effect on future development. The governance dimension focuses on the institutional compatibility of the proposed solutions, regulatory effectiveness, transition management, institutional endowment, capacity building, and the institutional adjustments required for implementing the solutions. The socio-political dimension needs to consider social acceptability and affordability issues, equity aspect, gender bias, political acceptability, local income generation issues, and behavioural changes required for the adoption of energy access solutions. The environmental dimension takes into account issues such as environmental desirability of solutions including benefits and adverse effects, resource sustainability and the social implications of environmental effects.

Whether or not a methodology takes such dimensions into account, and whether the approach is appropriate for general application needs to be reviewed. The objective of this paper is to identify alternative methodological options and analyse the appropriateness of various options for off-grid electricity supply. To the best of our knowledge, no such review exists, although reviews of decentralised supply or specific technologies or tools can be found.

The organisation of the paper is as follows: Section 2 provides a review of literature of techno-economic feasibility studies. Section 3 presents various analytical approaches such as indicators, optimisation, multi-criteria decision-making and systems approach, while Section 4 reviews some project-based literature (project reports, etc.). Section 5 then considers the appropriateness of alternative options for the purpose of off-grid projects. Finally, a concluding section captures the main findings of this paper.

2. A selected review of techno-economic feasibility studies

A large volume of literature of this sort is available that focuses on various technologies and country cases. The methodology in all these studies generally follows a common approach—assessment of technological appropriateness, evaluation of economic viability and determination of financial or other incentives required to make the project viable at a given location [59]. In the following paragraphs, only a brief review of a selected set of this literature is presented.

An early study analysing the grid-connected rural electrification options in developing countries can be found in [109]. As the demand in rural areas arises mainly from the use of domestic appliances, the load factor of domestic demand tends to be low, which emerges as the main problem for grid extension. Reddy et al. [93] argued that the magnitude of energy use is not the true indicator of development but the level of energy services provided should be considered for this purpose. This requires inclusion of decentralised and energy conservation options alongside energy supply options. Their study provided a comparative costing of grid-connected, off-grid and energy conservation systems in the Indian context. This study highlighted the importance of improved technology for rural energy services and provided a detailed evaluation of grid-connected, off-grid and energy conservation options using the life-cycle costing approach. Sinha and Kandpal [105] compared the cost of electricity supply through grid extension against the cost of supply from decentralised sources for rural India. This study considered the cost of extending the grid in terms of investments

[1] For a list of such tools and their characteristics see [10].

Table 1
Examples of HOMER application.

Reference and year	Technology application	Country of application
[22] 2010	Wind, PV, Wind–PV hybrid, and diesel generator.	Turkey—island example
[65] 2010	PV–diesel hybrid	Malaysia
[121] 2008	PV–diesel	Canada
[100] 2009	PV–Diesel, Wind–diesel, PV–Wind–Diesel	Maldives
[46] 2008	Wind–diesel hybrid	Algeria
[73] 2010	Wind–PV–Battery	Bangladesh
[115] 2011	Wind, solar, hydrogen	Turkey
[20] 2008, [21] 2009	PV, Diesel, Wind	Australia—energy supply options for a large hotel
[60] 2005	Wind, diesel, battery, fuel cell	Newfoundland, Canada
[101] 2007, [102] 2008, [103] 2009	PV–Diesel–battery	Saudi Arabia
[55] 2005	PV–Wind Hybrid power	Egypt
[74] 2008	PV, Micro-hydro, LPG generator, battery	Cameroon
[8] 2010	PV–wind hybrid	Ethiopia
[87] 2011	PV, wind, battery	Greek Islands

for the distribution network. It also considers the cost of grid electricity at various distances from the grid as well as for different levels of load factors and transmission-distribution losses. The cost of electricity supply from alternative sources is then considered and compared to see how the cost-effectiveness changes as the distance from the main grid increases, the load factor changes and peak demand increases. The study using data from late 1980s found that the decentralised solutions are viable in isolated, small villages with low load factors. Similarly, for villages located 25 km away from the 33 kV grid, decentralised options become viable. It might be useful to undertake such a study using more recent data and taking other country examples.

Bernal-Agustin and Dufo-Lopez [9] have performed an evaluation of the grid-connected solar PV system in the Spanish case. The study analysed the economic and environmental benefits of a PV project considering the net present value and payback periods. The paper considered the initial cost of the grid-connected PV system (i.e. the cost of the generator, the cost of the inverter, and the cost related to installation) along with any subsidy that is available to the investor. The net cash flow generated by the project per year is estimated taking income and expenses into consideration. Income is generated either by selling electricity to the grid or by reducing electricity purchase through auto-consumption of electricity generated through the PV system. Expenses include costs related to operations and maintenance of the system, insurance and financing the project. Given the cash flow occurs over the lifetime of the project and the investment is an initial cost, the net present value of the investment is considered assuming a life of 25 years for the project. The paper then applies this to a case in Zaragoza (Spain) and analyses the NPV and payback period for different electricity prices, interest rates, and subsidy sizes. The paper also considered the environmental benefits of PV electricity by considering the amount of emissions avoided and CO_2 emission mitigated. It then estimated the avoided costs of externality in monetary terms considering different scenarios of electricity substitution by the PV system (e.g. avoidance of thermo-electric power, power from sub-bituminous coal, etc.).

Chakraborti and Chakraborty [17] analysed the case of solar PV for an island use in Sagar Dweep, India. The study considered PV and grid extensions as alternative systems and evaluated the options from economic and environmental perspectives. The study shows that grid extension over long distances is not cost-effective. Other such studies include [63,91] which have considered the optimum plant size and cost of biomass use in Western Canada and the optimal mix of energy for a rural application in India. Gulli [43] on the other hand used the social-cost benefit analysis to compare the centralised and small distributed generation. Schmid and Hoffmann [99] analysed the feasibility of replacing diesel generating stations by solar PV–diesel hybrid systems in the Amazon region of Brazil.

In the following paragraphs, two examples are provided – a PV-based system and a wood-fuel system for rural application – to capture the essential features of techno-economic analysis. While other applications are also available, for brevity only two are reported here.

2.1. PV power supply

Rabah [89] analysed Kenya's potential for electricity generation using solar photovoltaic systems. The study used the following approach:

- Solar radiation information at different sites—To analyse the solar energy available from the sun's radiation four sites were used across Kenya. The required data was estimated from meteorological data either at the site or from a nearby site, which has similar irradiance. The analysis also included the tilt angles of solar PV, ranging from latitudes $\pm 15^{\circ}$.
- PV sizing—To determine the best geographic location for solar energy technologies, the analysis used the isotropic distribution model. The overall statistical database was analysed and then indexed and finally scanned to find for each station, the number of times in the eight-year period, that the radiation fell in the various radiation levels. The study used mono-crystalline and amorphous cells of 900 and 2610 cm^2, respectively. The system was sized to meet certain demand.
- Storage system design—By knowing the variability, storage system could be sized, so that energy could be provided during cloudy days and nights. Battery sizing was calculated based on the number of days of storage desired. A storage day referring to the amount of capacity a battery has supply power, without receiving any power input. Direct current is used for transfer and storage.
- Cost of electricity supply from the system—The study used the life-cycle cost approach to compare the cost of the solar system against that for a diesel generator of appropriate size. The cost of generating equipment, operating costs and maintenance costs over the lifetime of the project were considered and compared. The payback period, total costs and cost per unit of supply were used as the indicators for cost comparison.

The study used the above methodology to a hypothetical case and demonstrated its applicability.

2.2. Wood-fuel-based power

Ghosh et al. [38] presented a study of wood-fuel-based off-grid power supply in a remote Indian island. The study highlighted the technical performance of the largest biomass gasifier in India and compared its performance to that of a diesel plant.

Data sources were empirical as well as collected from secondary sources. To study the effect of variation in electrical load on diesel substitution, experiments were carried out for 30 days during January–March 1998. Electricity generations and per day wood and diesel consumption data were collected from the daily log book of the power plant for 30 months (July 1997–December 1999). Project details and other techno-economic components were obtained from Gosaba Rural Energy Co-operative Society (GRECS) and West Bengal Renewable Energy Development Agency (WBREDA).

A total of 60 consumers (about 15% of the total connections) were selected from the consumers' list (using systematic random sampling technique) and surveyed through personal interview method to gather the required relevant information. A formatted questionnaire was used to record the primary information. Environmental pollution load per kWh of electricity generation has been estimated stoichiometrically.

The study measured the percent of diesel replacement against different electricity loads for the Gosaba power plant. Substitution of diesel by gasifier gas first increases with the increase in load, reaches maximum at 58% load condition, then decreases at a lower rate. Diesel replacement obtained at the optimum load condition was 64%.

Households, motivated to conserve wood-fuel that provided additional income by selling saved wood-fuel to the electricity generator, adopted improved chulas (stoves). This behavioural change was noticeable and led to utilization of commercial energies and wood-fuels more effectively.

The cost of generation of 1 kW-h of electricity from the biomass power plant was estimated considering two scenarios—the reference year (1999) and the future year (2012). The cost parameters like load, number of hours of operation per year, capital cost, fuel cost, labour cost, cost of O&M and specific fuel consumption were obtained from actual data provided by WBREDA and GRECS. The life of the power plant and rate of interest on the capital investment has been assumed as 20 years and 6% per annum, respectively.

Sustainability of such a power plant has been analysed with respect to electricity demand, biomass supply and management of the plant. For continuous supply of input wood-fuel and also to avoid degradation of existing forests, energy plantation in 75 ha of waste land has been done along with the setting up of the power plant. At present, wood-fuel of the Leguminoscal family are being supplied from local sawmills. Plants of mangrove species have been planted in the site which is favourable to highly saline site condition but the yield of mangrove trees is lower (6 t/ha/year) than that of energy plantation (30 t/ha/year), which can affect long-term availability of fuel.

The study also estimated the environmental effects of the wood-fuel-based power plant in terms of air pollution. It found that SO_2 and NO_2 emissions increased because of higher pollutant load of wood-fuel.

3. Analytical approaches

In this section, a number of alternative approaches are presented that are found in the literature to analyse and decide the appropriate energy systems for rural areas. First, the indicator-based approaches are considered. This is followed by optimisation techniques, multi-criteria approaches, and systems analysis.

3.1. Indicator-based analysis

Three sets of indicator-based approaches are considered below, namely the levelised costs, weighted scores and sustainability indicators.

3.1.1. Levelised cost of supply

The levelised cost of supply is a common indicator used for comparing cost of electricity supply options. The levelised cost is the real, constant cost of supplying electricity that if recovered from consumers over the lifetime of the plant would meet all costs associated with construction, operation and decommissioning of a generating plant. This generally considers capital expenditures, operating and maintenance costs, fuel costs, and any costs involved in dismantling and decommissioning the plant. It can also consider the external costs and other relevant costs such as costs of back-up power in the case of intermittent energies. This indicator has been routinely used to analyse the cost-effectiveness of renewable energy options compared to other conventional energies. Examples include IEA [49,50], Royal Academy of Engineering study [95], CERI [16], and SunPower Corporation [111].

However, care has to be taken in using this method due to a number of factors:

- First, the levelised cost is calculated based on a specific rate of utilizationutilization (capacity factor) of a technology. Technologies with similar utilization rate can be easily compared using this method but technologies with different load profiles or loading patterns can give misleading results. For example, if a technology is used for base load and the other for peaking purposes, the levelised cost for the base load plant will always be favourable due to higher level of utilization.
- Second, in many cases, the variability of fuel costs is inadequately captured (or underestimated), making fossil-fuel-based plants more cost-effective.
- Third, for non-firm supply technologies, the cost of back-up or standby power could be inappropriately considered.
- Finally, this often ignores the external costs related to fossil fuel use, thereby putting the renewable energies at a disadvantage.

For decentralised electricity supply in developing countries, the levelised cost approach has been used in a number of studies. Banerjee [7] has presented a detailed study of cost estimations in the Indian context. Similarly, Noumi et al. [76,77,78] and Rana et al. [92] presented cost estimations for specific technologies in the Indian context.

Nouni et al. [75] has used this approach to identify the potential areas for decentralised electricity supply in India. They considered the delivered cost of electricity supply for different load factors and for villages located within a radius of 5–25 km from an existing 11 kV substation for two cases: plain terrain and hilly terrain, where the cost of local distribution tends to be higher. They also considered the cost of supply from decentralised renewable energy options. Considering typical village load data from 1991 Census statistics, they estimated that the average peak load of a remote rural household to be 0.675 kW. Considering the population of villages, they suggested that villages with less than 50 kW peak load could be considered for decentralised electricity supply through renewable energy technologies. The authors then considered the trade-off between grid extension and off-grid supply to find the cost-effective electricity supply option for remote villages. While this provides a framework of analysis from the cost of supply perspective, the analysis does not consider the external costs related to fossil fuel use, cost of security of supply, cost of stand-by power for renewable energies. Accordingly, the study is likely to favour fossil fuels and undermines the potentials of renewable energies.

Kolhe et al. [61] presented a life-cycle cost comparison between a stand-alone PV system and a diesel power plant in India. The study followed an approach similar to levelised costs but derived these using specific parameters for diesel plants and PV systems.

Table 2
Levelised cost for renewable energy technologies (2005, US cents/kWh).

Technology		Rated output (kW)	Levelised cost components				
			Capital	Fixed O&M	Variable O&M	Fuel	Average
Solar PV		0.05	45.59	3	13		61.59
		0.3	45.59	2.5	8		56.09
		25	42.93	1.5	7		51.43
		5,000	40.36	0.97	0.24		41.57
Wind		0.3	26.18	3.49	4.9		34.57
		100	13.55	2.08	4.08		19.71
		10,000	5.85	0.66	0.26		6.77
		100,000	5.08	0.53	0.22		5.83
PV–wind hybrid		0.3	31.4	3.48	6.9		41.78
		100	22.02	2.07	6.4		30.49
Solar thermal	with storage	30,000	10.68	1.82	0.45		12.95
	without storage	30,000	13.65	3.01	0.75		17.41
Geothermal	Binary	200	12.57	2	1		15.57
	Binary	20,000	5.02	1.3	0.4		6.72
	Flash	50,000	3.07	0.9	0.3		4.27
Biomass gasifier		100	4.39	0.34	1.57	2.66	8.96
		20,000	3.09	0.25	1.18	2.5	7.02
Biomass steam		50,000	2.59	0.45	0.41	2.5	5.95
MSW/Landfill gas		5,000	4.95	0.11	0.43	1	6.49
Biogas		60	3.79	0.34	1.54	1.1	6.77
Pico/Micro-hydro		0.3	14.24	0	0.9		15.14
		1	12.19	0	0.54		12.73
		100	9.54	1.05	0.42		11.01
Mini-hydro		5,000	5.86	0.74	0.35		6.95
Large hydro		100,000	4.56	0.5	0.32		5.38
Pumped storage		150,000	34.08	0.32	0.33		34.73

Source of data: [32].

Perhaps the most comprehensive study of alternative generating technologies suitable for energy access projects is found in an ESMAP technical paper [32]. This study presents a review of a range of technologies covering a wider spectrum of capacities—50 W–500 MW. The review is presented for 37 technologies (renewable, conventional and emerging) under three categories—off-grid, mini-grid and grid-connected electricity supply. The report provides the technical features of alternative technologies, presents alternative configurations that are used in practice and discusses the cost and performance assumptions of each technology used in the analysis.

The study has assessed the economics of the above technologies using the levelised cost method and presented the results for three different time horizons—2005, 2010 and 2015, to reflect the effect cost reduction in some technologies. The study also considers the effect of sensitivity of key variables on the economic viability of technological options. The costs of local distribution as well as long distance transmission are also considered where applicable. However, the study does not include the external costs and security of supply concerns for fossil fuels and stand-by power costs for renewable energies.

The levelised cost of electricity supply for renewable energy options is presented in Table 2, while the levelised cost of conventional/emerging electricity supply technologies is presented in Table 3. As can be seen from these two tables:

- The cost of off-grid options is generally higher than that of conventional energies;
- The cost of supply reduces as the size of plant increases. Electricity supplied from small-sized off-grid plants tends to cost much higher than the bigger sized plants of same technology;
- Some renewable technologies are either cost-effective or reaching cost-effectiveness.

However, the levelised cost approach, despite its wider use, is a one dimensional indicator and fails to capture any dimension beyond costs. In addition, the external costs due to environmental effects and security of supply were not captured in this study. This limitation needs to be kept in mind while using this comparator.

3.1.2. Weighted score system

Lhendup [66] presented a weighted score system where a number of aspects (such as technical, regulatory features, environmental and social aspects) related to rural energy supply options are considered. A set of indicators is then identified for each aspect and a weight is given based on the importance of the indicator. Each option is tested against a set of indicators and a score is given depending on the performance of the option against the indicator. The product of the score and the weight for a particular indicator gives the weighted score. The process is repeated for all indicators and the sum of the weighted scores for any option gives its total score. Supply options are ranked based on their weighted scores (Table 4). Lhendup [66] used a performance scale of 1 (low)–5 (high) and a total weight of 100 for 18 indicators. The paper explains the justification for each ranking in an appendix and indicates that the methodology can be implemented in a simple spreadsheet model.

Although this attempts to capture various dimensions in a simple way, there is some inherent subjectivity involved here in terms of weights attached and ranking given to each factor. However, if a participatory approach is used in deciding the weights and the ranks for a given locality or case, the usefulness of the tool improves. Factors can be varied depending on the local conditions but this also reduces the standardisation of the method to some extent. Moreover, the method only provides an initial choice decision but the detailed analysis and design of the system will still be required.

Table 3
Levelised cost of conventional/emerging technologies (2005, US cents/kWh).

Technology		Rated output (kW)	Levelised cost components				
			Capital	Fixed O&M	Variable O&M	Fuel	Average
Diesel/Gasoline generator		0.3	5.01		5	54.62	64.63
		1	3.83		3	44.38	51.21
		100	0.98	2	3	14.04	20.02
	Baseload	5,000	0.91	1	2.5	4.84	9.25
	Peakload	5,000	7.31	3	2.5	4.84	17.65
Microturbines		150	1.46	1	2.5	26.86	31.82
Fuel cell		200	5.6	0.1	4.5	16.28	26.48
		5,000	5.59	0.1	4.5	4.18	14.37
Combustion turbines	Natural gas	150,000	5.66	0.3	1	6.12	13.08
	Oil		5.66	0.3	1	15.81	22.77
Combined cycle	Natural gas	300,000	0.95	0.1	0.4	4.12	5.57
	Oil		0.95	0.1	0.4	10.65	12.1
Coal Steam with FGD and SCR	Sub-critical	300,000	1.76	0.38	0.36	1.97	4.47
		500,000	1.67	0.38	0.36	1.92	4.33
	Supercritical	500,000	1.73	0.38	0.36	1.83	4.3
	Ultra-Super Critical	500,000	1.84	0.38	0.36	1.7	4.28
Coal IGCC (without FGD and SCR)		300,000	2.49	0.9	0.21	1.73	5.33
		500,000	2.29	0.9	0.21	1.73	5.13
Coal AFBC (without FGD and SCR)		300,000	1.75	0.5	0.34	1.52	4.11
		500,000	1.64	0.5	0.34	1.49	3.97
Oil steam		300,000	1.27	0.35	0.3	5.32	7.24

Source of data: [32].

3.1.3. Sustainability indicators

Ilskog [51] presented a set of 39 indicators for assessing rural electrification projects. These indicators considered five sustainability dimensions—technical sustainability, economic sustainability, social/ethical sustainability, environmental sustainability and institutional sustainability. This is presented in Fig. 1.

Ilskog and Kjellstrom [52] present an assessment of rural electrification cases using 31 of these indicators. Each indicator was scored on a scale of 1–7, with 7 representing the best performance. The total score was obtained by simple averaging of the scores, implying that all indicators received same weight. The scoring was based on interviews with 800 randomly selected stakeholders and the performance comparison of projects was done using these indicator scores.

The paper considered that "the technical sustainability is facilitated if the technical infrastructure locally available meets the requirements of the technology installed, if the technology used can provide the service needed and if favourable technical performance leads to low costs for the services" Ilskog and Kjellstrom [52]. Table 5 compiles the indicators under five sustainability dimensions.

This method was clearly applied keeping the stakeholder participation in mind. Therefore, it is compliant with the participatory approach and can be used either at the local level or at a higher

Table 4
The criteria suggested by [66] and their weights.

Criteria	Weight	Ranking	
		1	5
1 Technical features	60		
1.1 Energy density of the system	8	Low	Very high
1.2 Ability to meet the anticipated demand	8	Not at all	Fully
1.3 Energy payback ratio	8	Low	High
1.4 Lifespan of the system	7	Short	Very long
1.5 Quality of supply	6	Poor	Very good
1.6 Weather and climatic condition dependence	6	Fully dependent	Not at all
1.7 Availability of local skills and resources	5	Not available	Available
1.8 Incremental capacity of the system	5	Difficult	Easy
1.9 Dependence on fossil fuels	4	Fully dependent	Not at all
1.10 Other infrastructure development	3	Required	Not required
2. Government regulations	15		
2.1 Tax incentives	5	Not provided	Provided
2.2 Regulation on use of local resources	5	Regulated	No regulation
2.3 Opportunity for private participation	5	Low	High
3 Environmental and social aspects	25		
3.1 Public and political acceptance	6	Not acceptable	Acceptable
3.2 Land requirement and acquisition	6	High	Low
3.3 Hazard rating	5	High	Low
3.4 Environmental pollutants	5	High	Low
3.5 Interference with other utility infrastructure	3	High	Low
Total	100		

Source of data: [66].

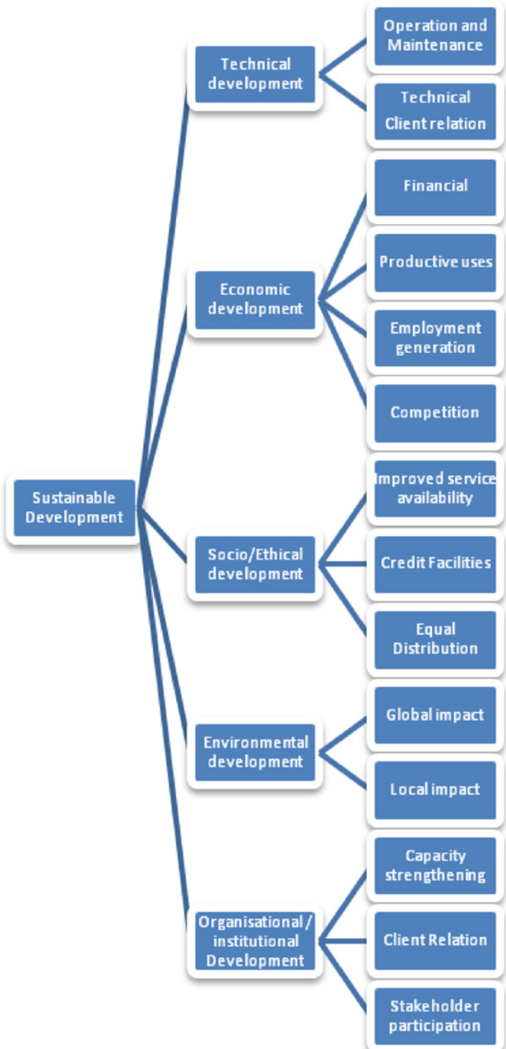

Fig. 1. Sustainability indicators process.

Source: [51].

level of aggregation. It can also capture qualitative factors and offers the flexibility that additional factors can be added while any factor that is not relevant for a given application can be removed. This can be easily adapted to include concerns of energy security and governance. However, several factors will require additional estimation/calculation and therefore will require a systematic tool to implement this approach. Again, the indicators are not the substitute for a detailed programme/project design.

3.2. Optimisation techniques

Optimisation has been widely used in energy analysis since the 1970s but applications for rural energy supply systems started in the 1980s. Parikh [80] presented a linear programming model to capture the interactions between energy and agriculture in rural areas of developing countries. The model considered 12 different energy sources and several conversion technologies. It captured the supply and demand for energy and agricultural outputs to find an optimal mix for a given rural condition. Ramakumar and co-workers [91] developed a linear programming model for integrated rural energy systems. The idea is simple here—the system will be designed to minimise the total cost subject to a number of constraints related to energy availability, energy demand, and other technical/system constraints. There were many different methods

Box 1: Equations used by Akella et al. [2].

Minimise	$Z = 1.50\text{MHP} + 15.27\text{SPV} + 3.50\text{WES} + 3.10\text{BES}$
Subject to:	$\text{MHP} + \text{SPV} + \text{WES} + \text{BES} = D\,\text{kWh/yr}$
	$\frac{\text{MHP}}{0.9} \le 128,166\,\text{kWh/m}^2\text{/yr}$
	$\frac{\text{SVP}}{0.9} \le 22,363\,\text{kWh/m}^2\text{/yr}$
	$\frac{\text{WES}}{0.80} \le 15,251\,\text{kWh/m}^2\text{/yr}$
	$\frac{\text{BES}}{0.85} \le 641,385\,\text{kWh/m}^2\text{/yr}$
	$\text{MHP,SPV,WES,BES} \le 0$

Source of data: [2].

of optimisation used to analyse IRES namely: Linear programming, Geometric programming, Integer programming, Dynamic programming, Stochastic programming, Quadratic programming, Separable programming, Multi-objective programming, Goal programming and Hybrid methods. The model presented in [90] was suitable for stand-alone systems. Further extensions of this model to include a knowledge-based design tool and other factors such as power reliability (loss of power probability) and scenario design are presented in [6] and [90].

Sinha and Kandpal [106–108] designed an optimisation model for rural energy supply considering lighting, cooking and irrigation demands. These models were applied to an Indian context to analyse the cooking, lighting and irrigation needs of rural areas and this showed how such a technique can be effectively used as a decision tool. These models considered a number of alternative technologies with different cost characteristics and found the optimal combinations using linear programming.

Iniyan and Jagadeeshan [53] developed an optimal renewable energy model (OREM) which considered 38 different renewable energy options. The model minimised the cost/efficiency ratio and used resource availability, demand, reliability and social acceptance as constraints.

Devdas [23–26] presented a linear programming model for analysing rural energy for local-level development. The program optimised the revenue of rural output subject to energy and non-energy constraints. The model was applied to the District of Kanyakumari of Tamil Nadu, India.

Parikh and Ramanathan [81] presented the INGRAM model to analyse the interactions between energy, agriculture and environment in rural India. This program maximised the net revenue of the rural energy system subject to constraints that included crop residue balance, animal feed balance, dung balance, fertiliser nutrients balance, as well as energy balance to ensure adequate supply to meet the demand. The model was calibrated for the year 1990–1991 and applied for the year 2000. Although this is not a rural energy supply model per se, it incorporated elements that are relevant for a sustainable rural energy system development, although it did not consider the use of modern renewable energies in the analysis.

Akella et al. [2] used an optimisation framework to analyse the optimum renewable energy use in a remote area in India. The paper considered solar photovoltaic systems (SPV), micro hydropower (MHP), biomass energy supply (BES) and wind energy supply (WES). The model provides the least cost combination of different renewable energies that could be used to meet the need. However, the model considers the overall energy use in the village and does not consider the projects that would be used to supply such energies. The model used the following equations (Box 1) where Z is the total cost of providing energy, MHP, SPV, WES and BES represent four renewable resources indicated above. All sources are used to meet the demand subject to availability constraints. The problem was solved using Lindo and Homer. The HOMER

Table 5
Indicators used for rural electrification analysis.

Technical sustainability	Economic sustainability	Social/ethical sustainability	Environmental sustainability	Institutional sustainability
Operation and maintenance—conforms with national standards	Financial perspective—profitability (%)	Improved availability of social electricity services—number of street lights in the area, number per 1000 population	Global impact—share of renewable energy in production (%)	Capacity strengthening—share of staff and management with appropriate education (%)
Technical losses (%)	Financial perspective—O&M costs (USD/kWh)	Credit facilities—Micro-credit possibilities available for electricity services connection (yes/no)	Global impact—Emission of CO_2 from production ($kgCO_2$/kWh)	Degree of local ownership (%)
Technical client-relation issues—daily operation service (%)	Financial perspective—Costs for capital and installation (USD/kWh)	Equal distribution—share of population with primary school education (%)	Local impact—share of electrified households where other energy sources for lighting has been replaced (%)	Number of shareholders (number)
Technical client-relation issues—availability of services (%)	Financial perspective—Share of profit set aside for reinvestment (%)	Share of population with access to electricity (%)	Local impact—share of electrified households where other energy sources for cooking main meals has been replaced (%)	Share of women in staff and management (%)
	Financial perspective—Tariff lag (USD, kWh)	Share of electricity consumers in high income category (%)	Any serious local environment impact identified (yes/no)	Number of years in business (number)
	Development of productive uses—share of electricity consumed by business (%)	Subsidy offered for electricity services (USD, kWh)		Client-relation—Share of non-technical losses (%)
	Share of electricity used by households for income generating activities (%)			Level of satisfaction with energy services (%)
	Competition—number of electricity service organisations in the area			Stakeholder participation—Auditing of reports on an annual basis (yes/no)

Source of data: [52].

analysis produced somewhat higher results due to the fact the software takes into account the cost of the local grid, cost of batteries and cost of conversion, while LINDO only considered the renewable system costs.

A very similar study was reported by Kanase-Patil et al. [56] where the case study was performed at a different location in India. This study considered micro-hydro, biomass, biogas, PV, and wind. A number of alternative scenarios have been presented and the least cost supply option is determined through the optimisation process. The optimisation programme was run using Lingo and HOMER packages.

Howells et al. [48] presented a study of a hypothetical, non-electrified, low-income South African village using MARKAL/TIMES—an optimisation model used for deciding the least-cost option for meeting the energy needs of the village. In contrast to other models, this application considered the entire range of end-use energy demand—cooking, lighting, space heating, water heating, refrigeration and other. It also considered electricity, diesel, LPG, solar, wind, candle, paraffin, coal and wood. The study suggests that such a detailed analysis is feasible. Such a framework can be used to capture multiple objectives—such as cost minimisation, minimisation of environmental effects, etc. It could capture the dynamic aspect of energy transition by considering a long-term perspective. But data availability is a constraint—especially data on appliance stocks, efficiencies, is not readily available. The model complexity increases as more technological options are included and the long-term dynamics is considered.

While the purpose of the optimisation tools is to select the optimal solution, often the results tend to be highly sensitive to the initial conditions and key assumptions used in the analysis. This can be a problem in the rural context where the information is less accurate and weak, and often approximation or guesses have to be resorted to. The optimisation tools also generally fail to capture the conflicting nature of issues involved in the decision making. Moreover, the assumptions of economic rationality of decision makers and the users may not hold as well. Moreover, the focus of these models has been on technical and to some extent economic dimensions. The social and governance dimensions have often been neglected in the optimisation approach. This reduces the usefulness of the tool to some extent, although for the system configuration this approach can still be relied on.

3.3. Multi-criteria decision-making method

The multi-criteria decision making (MCDM) is a decision support system that is used to capture multiple dimensions of a project or a policy, some of which may be conflicting with each other. There are three schools of thoughts in this area—the American School (or value measurement models), the European School (or outranking models), and the goal, aspiration reference level models [68]. The American school focuses on the Analytical Hierarchy Process and multi-attribute value/utility theory. This assumes that the decision maker is aware of the preferences and can express and rank them unambiguously. On the other hand, the European school does not assume full knowledge of preferences by the stakeholders and is therefore less restrictive. The third category on the other hand tries to find alternative solutions that are closest to achieving a desired goal or aspiration level (e.g. Silvio and Nakata [104]). These methods compare options relative to an ideal solution and the option closest to the ideal is chosen.

Each of these has been applied to energy and renewable energy issues—Greening and Bernow [42] point out the potential of MCDM

in energy and environment studies, while Wang et al. [119] present a recent review. Some other studies include Pohekar and Ramachandran [83], Diakoulaki et al. [27], Loken [68] and Oberschmidt et al. [79]. Some studies have also applied these techniques to decentralised energy systems. A brief review of these approaches and applications to rural energy issues is presented below. Loken [68] insisted that in choosing an appropriate MCDM approach, it is better to avoid "black-box" models as they are poorly understood by the decision makers. Transparent approaches generate better acceptability of results and outcomes as decision makers trust the results.

3.3.1. AHP method

The analytical hierarchy process is a powerful and flexible decision-making process developed by Saaty [96,97] that is used to solve complex problems involving interactions of different criteria across different levels. It is a multiple criteria decision-making technique that allows subjective as well as objective factors to be considered in decision-making process. The AHP allows active participation of decision makers/stakeholders in reaching agreement, and gives managers a rational basis on which to make decisions.

The AHP is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution ([117]. AHP is a problem-solving framework and a systematic procedure for representing the elements of any problem [98]. AHP is based on the following three principles: decomposition, comparative judgements, and synthesis of priorities.

Formulating the decision problem in the form of a hierarchical structure is the first step of AHP. In a typical hierarchy, the top level reflects the overall objective (focus) of the decision problem. The elements affecting the decision are represented in intermediate levels. The lowest level comprises the decision options. Once a hierarchy is constructed, the decision maker begins a prioritisation procedure to determine the relative importance of the elements in each level of the hierarchy. The elements in each level are compared as pairs with respect to their importance in making the decision under consideration. A verbal scale is used in AHP that enables the decision maker to incorporate subjectivity, experience, and knowledge in an intuitive and natural way. For pair-wise comparison, a scale proposed by Satty [96] is commonly used (Table 6). After comparison matrices are created, relative weights are derived for the various elements. The relative weights of the elements of each level with respect to an element in the adjacent upper level are computed as the components of the normalized eigenvector associated with the largest eigen value of their comparison matrix. Composite weights are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a normalized vector of the overall weights of the options. The mathematical basis for determining the weights was established by Saaty [95].

Dyer and Forman [30] describe the advantages of AHP in a group setting as follows: (1) both tangibles and intangibles, individual values and shared values can be included in an AHP-based group decision process, (2) the discussion in a group can be focused on objectives rather than alternatives, (3) the discussion can be structured so that every factor relevant to the discussion is considered in turn, and (4) in a structured analysis, the discussion continues until all relevant information from each individual member in a group has been considered and a consensus choice of the decision alternative is achieved. A detailed discussion on conducting AHP-based group decision-making sessions including suggestions for assembling the group, constructing the hierarchy, getting the group to agree, inequalities of power, concealed or distorted preferences, and implementing the results can be found in [39,96].

Table 6
AHP pair-wise comparison scale.

Score	Description
1	Equally preferred
3	Weak preference
5	Strong preference
7	Very strong or demonstrated preference
9	Extreme importance
2, 4, 6, 8	Intermediate values

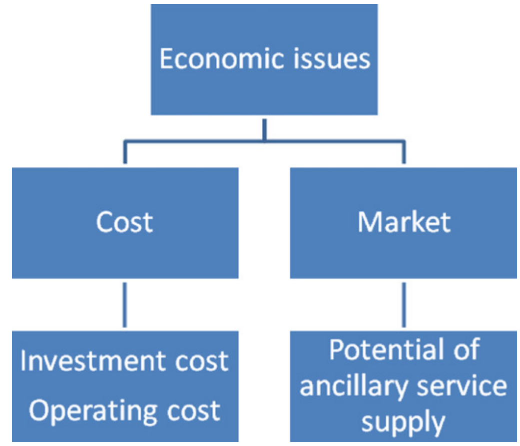

Fig. 2. Economic factors considered by Zangeneh et al.
Source: [124].

AHP is the most commonly used MCDM approach. Zangeneh et al. [124] used the AHP method to prioritise distributed energy options using a case study of Iran. The first level set the prioritisation goal. At the second level, four factors are considered—technical, economic, environmental attributes and regional primary energy resources. At the third level, sub-criteria for each of the factors are introduced. For economic aspects, two factors are considered: costs and market (Fig. 2). For cost, two further factors are considered—investment cost and operating cost. For market, two other factors are considered—potential of ancillary service supply and potential of ancillary service supply.

For technical issues, three factors are considered—operational issues, structural issues and technical requirements (Fig. 3). Six factors are considered under operational issues—power quality, forced outage rate, response speed, efficiency, start-up time, and capacity factor. Under structural issues four factors are considered—footprint, lifetime, modularity and installation lead time. Similarly, three factors are included in the technical requirement category—maintenance, domestic technical knowledge and interconnection equipment.

Under the environmental dimension, three factors have been considered (Fig. 4): noise emission, pollution emission and aesthetics. While noise and aesthetics did not have any further factors, under pollution emission, five factors are considered—PM10, SO_2, CO_2, NO_x and CO.

The case study considered PV, wind, fuel cell, micro-turbine, gas turbine and diesel engines as alternative technologies. The prioritisation was done based on a survey of expert views (51 participated but 37 results were retained). The analysis was performed using Expert Choice software. The paper presented the results of the prioritisation exercise with detailed tabulation of criteria values at each level.

Other studies using AHP for energy analysis include Wang et al. [118], Wang and Feng [120], Limmeechokchai and Chawana [67], and Kablan [54].

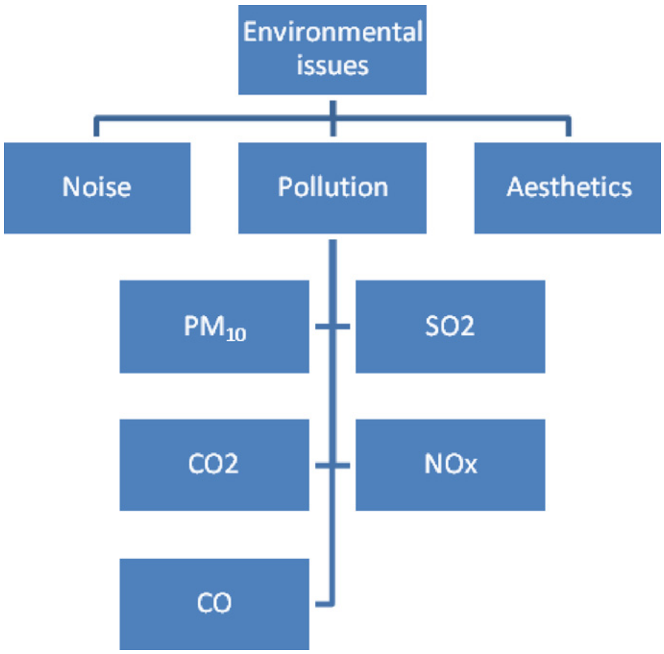

Fig. 3. Technical factors considered in [124].

Source: [124].

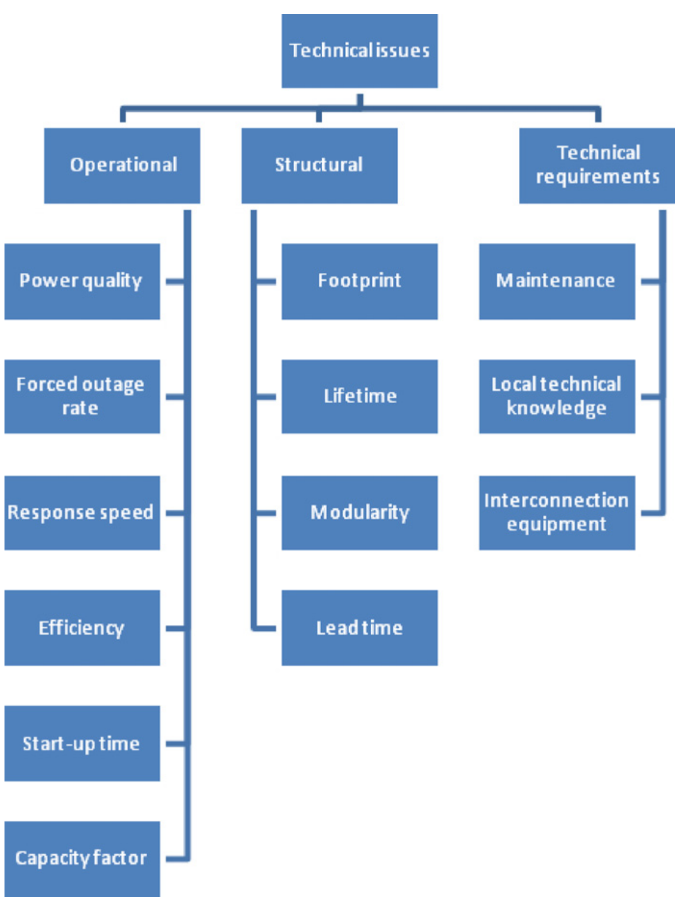

Fig. 4. Environmental factors considered in [124].

Source: [122].

3.3.2. Multi-criteria decision making for renewable energy sources (MCDM-RES)

Polatidis and Haralambopolous [85] presented an integrated renewable energy planning and design framework that they applied to a Greek island in the Aegean Sea. The planning activity is considered to be multi-dimensional activity that takes technical, economic, environmental and social aspects into consideration. The authors highlight the complexity of energy planning process due to the presence of structural aspects, multiplicity of actors and multi-dimensional sphere of interactions. This is captured in Fig. 5. In addition, they are mindful of the fact that technologies and decision-making processes have further temporal and spatial dimensions, and these aspects along with social dynamics have to be taken into account.

Given the presence of multiple objectives and multiple actors, the authors use a multi-criteria decision-making framework. The decision-making process involves the following eight steps:

- Problem identification and initial data collection;
- Institutional analysis and stakeholder identification;
- Creation of alternatives;
- Establishing evaluation criteria;
- Criteria evaluation and preference elicitation;
- Selection of the MCDA technique;
- Model application;
- Stakeholder analysis of the results and feedback.

At the last stage, where the results are shared with the stakeholders, if the level of acceptance is found to be low, the process will be repeated to generate a more acceptable outcome and the solution can then be implemented.

The application to the Greek case showed how the above steps were followed. Four alternative options were considered—(1) installing a 2 MW diesel generator, (2) a 4 MW hydro plant in conjunction with four wind turbines of 0.6 MW each, (3) a 4 MW hydro plant in conjunction with eight wind turbines of 0.6 MW each, and (4) a 2 MW diesel generator along with a 4 MW hydro plant and 12 wind turbines of 0.6 MW. The evaluation criteria were initially developed through a literature review. This was then discussed with the stakeholders and finalized. These are presented in Table 7 below. The analysis was performed using PROMETHEE II package, a widely used program following the European tradition of MCDM analysis. The PROMETHEE suit of packages has been used in energy planning decision-making (see Table 7 for a list of such applications).

Many other studies have been reported in the literature in the field of rural energy or renewable energy supply using the MCDM approach. Such studies have covered a wide range of applications (Tables 8a and 8b) and have used established software packages or have presented alternative tools.

Cherni et al. [18] presented a multi-criteria analytical tool SURE for rural livelihood decision analysis which can be used to decide appropriate rural energy supply options that can be used for enhancing rural livelihood. The package was developed through the support of DfID and incorporates technical and non-technical aspects such as financial, social, human and environmental dimensions. The paper reports the application of the model to a Colombian rural community.

Cherni et al. [18] indicate that although MCDM has been used in analysing rural energy issues, the technical aspect received a privileged treatment in the decision-making process. The issue of sustainable rural energy supply and rural livelihood issues received little attention. SURE they claim have overcome this challenge. Buchholz et al. [12] argue a similar participatory process for wider use of biomass energy in a sustainable energy context.

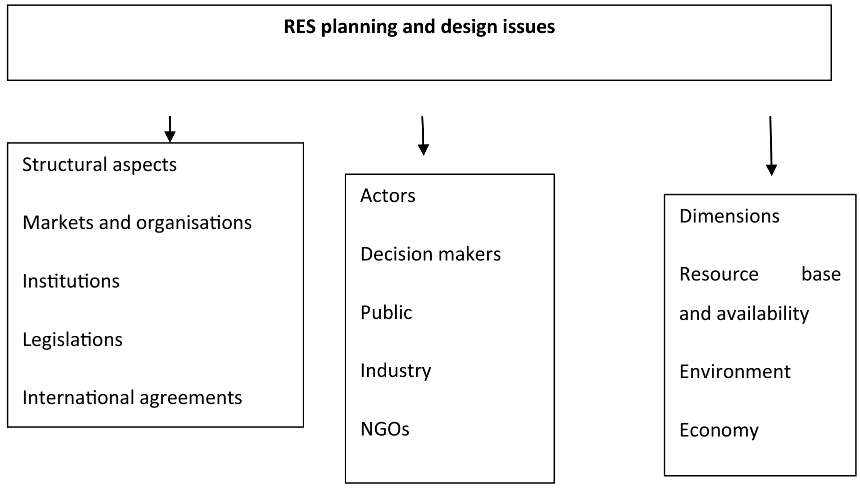

Fig. 5. Renewable energy planning issues. RES planning and design issues.

Source: [85].

Table 7
Evaluation criteria used in the analysis.

Energy resource criteria	Economic criteria	Environmental criteria	Social	Technological
Amount of imported oil avoided (toe/year)	Payback period (years)	Land used by the project (m^2)	Employment creation	Reliability and safety
Potential for reducing blackouts (% of peak load)		Compatibility with other activities	Public acceptance	
	NPV of investments (€)			
Amount of electricity produced (kWh/year)	Installation cost (€/kW)	Noise creation		
	Operational costs of electricity generation (€/kWh)	Visual impact		
	Net economic benefit for the community (€/year)	Construction of electricity networks and access roads (km)		
	Entrepreneurial risk (risk of project failure)	CO_2 reduction potential (tons of CO_2 avoided)		

Source of data: [85].

Table 8a
List of applications of PROMETHEE in the area of energy.

Application field	References
Comparing CSP (Concentrating Solar Power) technologies	Cavallaro [14]
Regional energy planning with a focus on renewable energies	Polatidis and Haralambopoulos [86], Terrados et al. [112], Tsoutos et al. [114]
Analysis of national energy scenarios in Greece with a focus on renewable energies	Diakoulaki and Karangelis [28], Georgopoulou et al. [36]
Designing energy policy instruments	Doukas et al. [29], Madlener and Stagi [69]
Evaluation of different heat supply options	Ghafghazi et al. [37]
Prioritisation of geothermal energy projects	Goumas and Lygerou [40], Goumas et al. [41], Haralambopoulos and Polatidis [44]
Participatory analysis of national renewable energy scenarios in Austria	Kowalski et al. [62], Madlener et al. [69]
Evaluation of biomass collection and transportation systems	Kumar et al. [64]
Siting of hydropower stations	Mladineo et al. [72]
Comparing cooking energy alternatives	Pohekar and Ramachandran [83]
Evaluation of residential energy systems	Ren et al. [94]
Comparing energy technologies based on renewable, fossil or nuclear resources	Topcu and Ulengin [113]
Evaluation of energy research projects	Tzeng et al. [116]

Source of data: [79].

Table 8b
Application of MCDM in rural energy issues.

Reference	Area of application	Tool/Method
Cherni et al. [18]	Rural energy supply for rural livelihood	SURE
Haurant et al. [45]	PV on farming land in an island	ELECCTRE
Georgopoullou et al. [35]	Renewable energy planning in a Greek island	ELECTRE III
Kablan [54]	Rural energy in Jordan	AHP
Pokharel and Chandrashekar [84]	Rural energy	Goal programming (STEP)
Karger and Hennings [57]	Sustainability of decentralised options	AHP

Clearly, the MCDM approach is relevance for off-grid electrification decision-making. However, as discussed above, the approach has often not paid adequate attention to rural energy supply issues, except in a few special cases. In the rural context the usefulness of complex, black-box type tools can be limited due to difficulties in appreciating such tools. Therefore, tools that can be easily communicated with the local participants and can generate better confidence in the users are more likely to be preferred. Although MCDM tools can be designed for such uses, the available tools may not always fall in this category.

3.4. Systems analysis approach

For any analysis of a rural energy system, it is important to understand and capture the complex interrelationships that exist with the society, environment, technologies and governance aspects. One of the main issues related to any decision-making is the failure to incorporate appropriate feedback from various interactions. Also, the analysis has often been carried out at a highly aggregated level, which in turn removes the possibility of capturing important issues or aspects that influence the system performance [110]. Further, additional issues related to conventional modeling-modeling include the following [88]:

- Inter-temporal interactions and feedback are not modeled explicitly;
- The disequilibrium framework for modeling is missing;
- Time delays and other distortions of the energy system variables are not explicitly modeled;
- Non-linear responses to actions are not explicitly represented.

The systems approach has attempted to remedy this problem by understanding the information feedback structures in systems [19,34] and by representing such feedbacks through casual loops and analyses them quantitatively. In the area of rural energy and rural electrification, various studies have been reported in the literature. For example, Alam et al. [5] reported a model for rural energy system of Bangladesh. The model considers crop production, biogas production, and rural forest and agro-based industries and analyses how output can be optimised to improve the quality of life. Similarly, Alam et al. [3] have reported an application of their previous model for farming in Bangladesh, while Alam et al. [4] reported the analysis of rural household energy use. The model incorporates feedback loops, non-linearity and time-lag features commonly found in real systems. Xiaohua et al. [123] presented a model to analyse the interaction between the rural energy system and the economy for a Chinese rural community. It considered a basic feedback structure of rural energy -economy and analysed the factors affecting rural energy use.

Although the system-based models hold a great potential for participatory decision-making, the limited examples available in the literature points towards a lack of appreciation and available capacity in this area. Clearly, more attention is required to make greater use of this potential tool.

4. Practice-oriented literature for decentralised RE supply analysis

The literature is also well developed for this category of studies[2] but we shall review four studies—Cabraal et al. [13], CEEP [15], ESMAP [31] and World Bank [122] as they include some form of frameworks for analysing off-grid energy supply.

[2] Two examples include [33] and [47].

4.1. Solar PV-based electrification in Cabraal et al. [13] study

This study focused on the best practices for household rural electrification using solar PV systems. The study reported a number of case studies and provided a framework for economic/financial comparison of alternative options for household electrification. The cash flow analysis using economic and financial evaluation methods was used as the framework of analysis and was performed in Excel. An annex to the report enlists the following steps for such an analysis:

- Energy demand estimation: as electricity is used for lighting and appliances, the demand for these services has to be considered for decentralised electricity supply;
- Village selection criteria—identifying a set of conditions/parameters for village selection is the second step in the process. The parameters normally considered are number of households to be connected, distance from the grid, size and number of productive loads, and load growth prospects. Each of these factors affects the cost of supply and hence is an important consideration for supply decision;
- Alternative technology options—The third step is to identify alternative technologies that could be used to supply the energy service. The study considered kerosene/battery schemes, solar home schemes, isolated grid and central grid extension. The sizing of the alternative systems to satisfy the needs is also done at this stage;
- Least-cost comparison of options–This step provides the economic and financial cost comparison of alternative options using the cash flow method. The levelised cost of each option is calculated to determine the least cost option. The break-even analysis is used to identify the range of economic viability of alternative options for villages of different size (household numbers) and household density.

The study also evaluated the experience of a number of case studies by considering the technical, financial and institutional performances using a set of criteria. For technical evaluation, the factors considered were: system size selection, system quality, installation repair quality, training/maintenance, availability of spare parts, and battery recycling. For financial evaluation, the performance was evaluated based on credit supply, financial sustainability, system pricing, and tax/subsidy structures. For institutional performance, the institutional structure, marketing strategy, information dissemination, and sustainability of institutional structure were considered. The study while focusing on practical applications, has not reported any systematic tool for the distributed off-grid systems.

4.2. Worksheet-based tool in CEEP [15]

CEEP [15] relied on a worksheet-based package, called RREAD [Rural Renewable Energy Analysis and Design Tool] for RE system analysis for decentralised operations. The model considered—economic, social, technical and environmental aspects. The programme analyses the energy availability, technical viability, economic feasibility and social—environmental value of a PV, wind and PV–wind hybrid systems (see Fig. 6 for the model structure).

“The input module consists of six sets of data: resource data, load data, system configuration, capital and operating costs, financial data and policy scenario information (e.g., the existence of tax credits, subsidies, and program initiatives to internalize social benefits/costs, etc.). The resource, load data and system configuration data are used to evaluate the system's overall energy performance, including energy output, resource-load matching capacity and

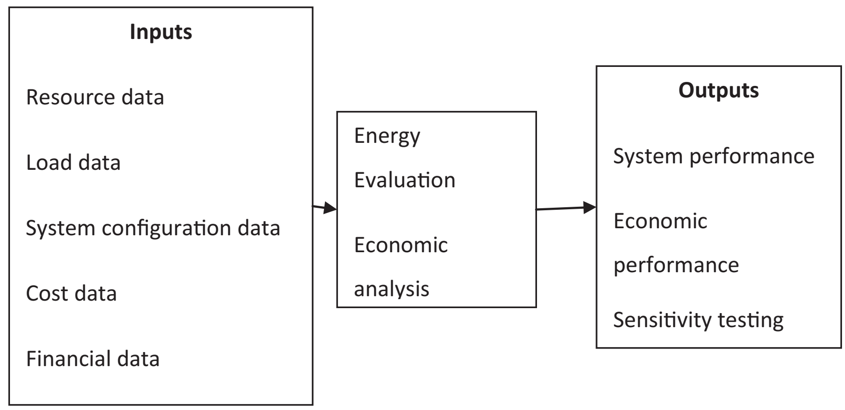

Fig. 6. Structure of RREAD.

Source: [15].

service reliability. Cost, financial and policy data measure the economic, social and environmental values of using renewable energy systems." [15].

This method was used to determine the levelised costs of supply for different systems under different conditions in China. The study then conducted a socio-economic analysis using a local survey. The report also used a logistic regression model to analyse the survey results. This study considered all relevant dimensions in a systematic way using a practical tool but it was designed only for PV-based supply. This limited technological choice is a constraint for its generic use.

4.3. *The ESMAP study [31]*

The ESMAP [31] study provided the best-practice guidelines for implementing decentralised energy systems for project managers. The decentralised option is an alternative approach to "production of electricity and the undertaking and management of electrification project that may be grid connected or not."

It provides a step-by-step approach to project implementation which focuses on five steps as indicated below:

- Step 1: Definition of institutional and regulatory environment—Key steps in this activity are:
  - Assessment of government commitment to decentralised energy supply;
  - Verification of legal provisions related to private sector involvement;
  - Identification of market barriers for DE;
  - Identification and assessment of technical capacity;
  - Identification and assessment of local financial institutions;
  - Identification of the role and responsibilities of the agency responsible for DE;
  - Identification of local institutions/NGO and their roles/responsibilities;
  - Assessment of private sector interest.

This stage will make sure the government commitment to the activity is enlisted and the institutional arrangement for decentralised energy services is established.

- Step 2: Market assessment and identification of project concept—This is the preparatory step for developing the project idea. Key steps include:
  - Collection and review of existing information and/or initiation of a market analysis;
  - Collation of market information and completion of market analysis;
  - Analysis of competing products or services;
  - Identification of cost of service and disposable income of consumers;
  - Identification of possible distribution paths;

This step provides market information that can be used in the next stage:

- Step 3: Appropriate technology and product choice–This step selects the appropriate technology option to provide a reliable and cost-effective supply to meet the local needs. Key steps include:
  - Identification of available technologies;
  - Energy demand estimation in terms of energy use, form, and quantity;
  - Determination of the most appropriate technology option;
  - Selection of a product delivery option;
  - Product testing and specification preparation;
  - At the end of this step, a tested product option is available for delivery.
- Step 4: Selection of a delivery mechanism—The study focuses mainly on two types of delivery mechanisms—cash and credit system or leasing through a dealer and delivery through an energy service company (ESCO). The key steps involved at this level are:
  - Assessment of credit availability;
  - Review of distribution infrastructure;
  - Assessment of affordability of decentralised energy options;
  - Selection of a product and its delivery channel;
  - Initiation of distribution channel establishment;
  - This step provides a delivery mechanism for an identified technology option and initiates the process for establishing the delivery of the product.
- Step 5: Review and evaluation of financial options–This step evaluates whether the financial sector is geared to meet the financing needs of decentralised supply and identifies appropriate options to meet the local needs. Key steps here include:
  - Identification of financial needs;
  - Evaluation of the rural banking system and the availability and cost of credit;
  - Mobilization of the banking sector;
  - Identification of local partners;
  - Identification of financing options and programmes;
  - Determination of the terms of financing.

This study covers the entire set of activities related to a decentralised energy supply and is quite generic in terms of technology

choice or country of use. It suggests a sequential framework of analysis with a detailed list of criteria that can be used in each step. Two areas are under-represented–environmental aspects and social dimension of the problem. Also, the potential for conflicts at each stage is not adequately captured.

4.4. The World Bank study [122]

World Bank [122] identifies the following critical factors for an off-grid project design:

- Comparing technology options—the first task is to determine the suitable technology option or options. The general guidance given is as follows:
- If the consumer size is small and dispersed, and if their main need is lighting, individual systems like SHS works; Other technologies for individual demand are pico-hydro systems work where water resources are available while wind home systems are now being piloted;
- Where consumers are concentrated and can be economically inter-connected, a mini or micro grid is commonly used. Diesel, RET or hybrid options are used.
- Social safeguards and environmental considerations–Although off-grid projects are generally environmentally beneficial, some components such as use of batteries can have some environmental effects. These need to be carefully integrated with the national policies on waste recycling and hazardous wastes. Similarly, off-grid projects must adhere to national guidelines or regulations on watershed protection, land use and land acquisition.
- Productive and institutional applications—Off-grid communities could engage in many productive activities such as agricultural production and processing, fishing, animal rearing if quality energy is provided. Similarly, institutional or community-level uses such as schools, clinics or community centres could form another main use of off-grid electricity. The project design should take advantage of such "systematic and pragmatic approaches" [33].
- Enhancing affordability–Generally, only 2–3% of the consumers are found to afford cash purchases of off-grid solutions. The customer base can be expanded to 20–30% with micro-credit. With leasing, the customer base can be increased to 40–50%, while long-term fee-for-service options could increase the customer base further. Subsidies, consumer financing, low-cost technology options and support to businesses and commerce can also be considered to improve affordability.
- Business models for off-grid solutions—The supply of off-grid solutions could be provided using a number of players—private entities, individuals, community-based organisations, NGOs and state agencies. Appropriate incentives are required to attract players into this business. Various alternatives have been experimented—including dealerships, Energy Service Companies (ESCO), leasing arrangements, medium term service agreements, community-based supply, and hybrid forms. The local market condition plays an important role in deciding the appropriate business model.
- Regulating the off-grid supply—This is an important aspect of the supply where the state has to play an important role to ensure that consumers are not overcharged and receive a quality supply. The regulatory framework for traditional grid supply may not be appropriate for such services and needs a special attention.
- International co-financing support—For providing access to energy using renewable energies, various co-financing options are available, including funding from the Global Environment Facility (GEF), Global Partnership for Output-based Aid (GPOBA), the Climate Investment Funds and the Clean Development Mechanism (CDM). These sources could be tapped to reduce the financial burden of the national agencies.

The elements of a sustainable off-grid electrification project are presented in Fig. 7.

Although the study provides a list of critical elements for a successful off-grid project, it does not provide a framework of analysis.

The above review shows that the practice-based literature has tried to address the off-grid electrification decision-making keeping the successful delivery of supply as the end objective. This whole system delivery approach makes this literature different from the rest where the focus was limited to project/technology choice decision, performance comparison or system selection components only. This suggests that a successful implementation of any off-grid electrification project or programme requires a careful planning of all related stages, which goes beyond just the technology choice or component selection decision. This set of literature also highlights the usefulness of simple, practical tools that can be easily used and managed by the users. Surely,

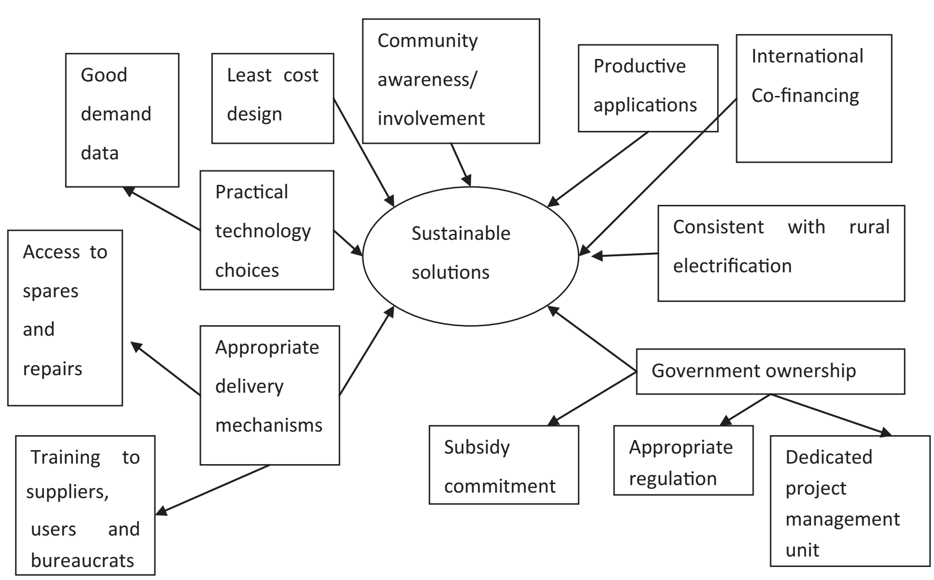

Fig. 7. Elements of a sustainable off-grid electrification project.

Source: [122].

this literature also suggests the growing divergence between the academic outputs and the practice-oriented works.

5. Critical evaluation of methodological options

Based on the above review of literature it is possible to identify a number of alternative options that can be considered for any off-grid electricity access provision project or programme. In this section, a number of alternatives are first presented along with their strengths and weaknesses.

5.1. Alternative choices

At least five options can be identified as candidates as indicated below:

- Option 1—a worksheet-based tool that provides a sequential analysis of various dimensions of an off-grid project where relevant indicators and decision analysis can be included;
- Option 2—An optimisation-based tool to identify and design the least-cost option, supplemented by a routine to take care of social and regulatory issues;
- Option 3—A multi-criteria decision-making (MCDM) tool;
- Option 4—A participatory systems approach;
- Option 5—A suitable combination of the above options to be decided and used on a case-by-case basis.

Option 1 has the advantage that it does not require any special skills and can be used by users easily. It is easy to develop and examples like RETSCREEN can be followed for the design purpose. Such a tool can be generic in nature so that a wide range of technological and local conditions can be easily catered to. Inputs and feedback from the local community can be incorporated in the data through stakeholder meetings. Such a tool can be easily hosted on the website for wider dissemination and use. However, the main problem with this option is that while it can capture technical, economic and environmental dimensions, the social and institutional aspects are more difficult to capture here explicitly. Moreover, the academic credibility of such a tool can also be an issue from the funding agency side–because it is unlikely that such a tool will be seen as a new frontier of research or knowledge creation. Further, as an off-grid project is the focus of analysis of such a tool, the analysis of mainstreaming of such options for national or regional policy-making cannot be performed using such a tool.

Option 2 can take different forms–either existing tools like HOMER could be adopted as the basic tool for the least-cost system design, or a new tool can be developed if the existing tools are found to be deficient for our purposes. The outcome can be further analysed and refined to take care of the regulatory and social dimensions. Similarly, two tools may be required to analyse the village level issues and national/regional dimensions. To capture social and institutional dimensions, additional routines will be required.

The advantage of an optimisation tool is its theoretical appeal from a cost-minimisation perspective. Such a tool can easily capture the technical, economic and environmental dimensions and it is now possible to seek optimal solutions to satisfy multiple objectives simultaneously. The framework is generally rigorous and will have academic credibility. The model could be designed to include user-defined inputs and multiple scenarios and sensitivity analyses can be easily performed. However, developing a new model can be time consuming and requires specialised skills. Running such a model generally requires special computer platforms (software) and such tools may not be easily transportable from one machine to another. There is also some hostility towards optimisation models due to their abstraction from the real-life experiences.

Option 3—A multi-criteria decision tool can provide an effective framework to capture all four dimensions of the project. The existing tools like PROMETHEE can be used or a specific tool for the project can be developed. The main advantage of this framework is its focus on participatory decision-making so that local community views and feedback can be easily included. It has the advantage that conflicting objectives can be considered and the solution tries to find the best compromise—not the optimal solution. It can also consider the qualitative factors that other methods cannot capture. It will have academic credibility as well. However, such an analysis will have to be supplemented by further studies to develop and design the project technically, evaluate the financial/economic robustness, and analyse the environmental and social dimensions. The approach requires special skills and may require special computing platforms.

Option 4—The participatory whole systems approach offers another viable alternative. This approach, as mentioned earlier, does not rely on an optimisation process but considers the local resources, constraints and the desires/expectations of the local communities to identify a viable option. As this method involves local communities in the decision-making and finds outcomes jointly with their support, the outcomes are likely to be more acceptable to the local population. Although, this approach will require a significant amount of capacity development, it is possible to make a distinct contribution in this respect.

Option 5—This option combines one or more of the above options to produce an effective tool that can overcome the weaknesses of each but take advantage of their strengths. A number of alternative possibilities can be considered here: one alternative is to adopt a multi-tool approach where worksheet-based, optimisation tools and multi-criteria decision tools are considered for various case studies and thereby develop skills and capacity for alternative tools. Another possibility is to apply two tools together—for example, a worksheet-based tool can be combined with the multi-criteria tool or a system optimisation tool can be combined with a MCDM tool. This has the appeal from a number of perspectives—academically, this can be a more credible option. This also removes the weaknesses of a single tool and acts as a check. Finally, from the capacity building and knowledge development perspective, this can be useful as well. However, this is a resource-intensive approach and has to be considered carefully.

6. Conclusions

This paper has reviewed a number of alternative methodologies that have been reported in the literature. The material covered included academic literature on case studies, specific tools such as indicators, optimisation tools and multi-criteria decision-making tools, and practice-based literature. Based on this review, it is found that most of the academic literature has focused on techno-economic and environmental dimensions of the problem, with technical system design and economic viability assuming the predominant focus. Only the MCDM approach appears to consider the social and institutional dimensions but this approach is insufficient to develop the system design and analyse the detailed viability of the system. The participatory, whole systems approach on the other provides a viable alternative but will require significant capacity development. The practice-based literature on the other hand has considered the relevant factors but has not necessarily focused on the development of an integrated analytical framework.

This paper has identified five options—a worksheet-based tool, an optimisation-based tool supplemented by further analysis of social/institutional dimensions, use of a MCDM tool, the participatory whole systems approach or a hybrid tool. The paper

recommends a hybrid tool that can be used in different case study situations. The hybrid option allows for the verification of results from alternative approaches and can complement the strengths and shortcomings of each approach. However, this can be resource intensive and therefore will require a careful consideration on a case-by-case basis.

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